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THE COLLINEAR COAXIAL ARRAY ANTENNA,(U)
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PROCUREMENT EXECUTIVE,
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ROYAL SIGNALS AND RADAR ESTABLISHMENT

Memorandum 3350

TITLE: THE COLLINEAR COAXIAL ARRAY ANTENNA

AUTHORS: D J Brammer D Williams

DATE: March 1981

SUMMARY

This memorandum describes the results of a numerical analysis of the Collinear Co-axial Array Antenna. The analysis using the Moment Method treats a variety of antennas ranging from the simple basic configuration to one with 10.7 dB gain. The effect of using lossy cable in the antenna construction is described and the antenna bandwidth is indicated.

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THE COLLINEAR COAXIAL ARRAY ANTENNA

D J Brammer and D Williams

1 INTRODUCTION

The Collinear Co-axial Array Antenna which when mounted vertically finds application in the central or base station of VHF/UHF mobile communication systems is described in the ARRL Antenna Handbook (1). The diagram, Figure 1a, shows the ARRL design. Features are the ease of construction and the possibility of getting substantial gain by repeating the centre section CD.

In this paper the antenna is analysed by the Moment Method. Various configurations are analysed and current distributions. gain, polar diagrams and impedances are calculated. The analysis is first carried out for simple configurations and is later extended to a case with 16 repeated centre sections and 10.7 dB gain. The effect of using lossy cable in the construction on the gain and the bandwidth is also investigated. In the process the ARRL design was found to be in error.

In addition an analysis is performed to discuss the extent to which current distributions must be uniform as well as in phase in order to achieve maximum gain in an extended linear array.

2 THE MOMENT METHOD

The method will only be outlined; a complete description of the method used here can be found elsewhere (2). The fundamental problem is to solve Maxwell's equations with the boundary conditions consequent upon the conductor system and the exciting sources to obtain the current distribution on the conductor system. In the present example a complication arises in the use of co-axial cable connecting parts of the conductor system. The cable inner conductors do not form part of the configuration of conductors which establishes the boundary condition. In Figure 1a, b, c, this co-axial cable system is shown in broken lines. The Moment Method analysis was performed using the NEC code written by the Lawrence Livermore Laboratories of the University of California. This code allows transmission line coupling of parts in the conductor system. The transmission line can be made lossy by replacing the cable connecting ports by networks with appropriate Y parameters. The NEC code uses a sectional basis function system in which the conductors are divided into segments, the current on the segment is expanded in three terms with dc, sinusoidal and co-sinusoidal terms. By adding a condition that the current due to one segment would be zero when extrapolated to the end of the next segment, it is possible to ensure continuity of both current and gradient of current and problems due to charge on segment junctions are avoided. The boundary condition that the tangential electric field be zero is applied at the middle of each segment. This results in a system of n simultaneous equations in n unknown current coefficients in the n segments. A solution of this matrix equation gives the current distribution from which polar pattern, gain, and impedance can be calculated.

In using the method an adequate number of segments must be used to describe the variation in current and this is equivalent to demanding that segments should not be longer than some fraction of a wavelength usually one eighth. In the present application segments are 6 cm long and at a frequency of 150 MHz; this is 0.03 λ. The primary output of the calculation is the current distribution on the conductors. From this far field radiation patterns and gains resulting from 1 Volt applied at the terminals can be calculated while the current in the driven segment enables the impedance to be deduced.

3 THE ANTENNA

Jasik (3) cites several antennas of the same type under the heading of VHF base station antennas. The Franklin antenna is related. The object of these designs is to maintain a current distribution with as near as possible uniform phase and amplitude on the conductors. In the present case this is achieved by connecting the points (at C D Figure 1a) by half wavelengths of cable with a reversal of the connections so that the driving voltages at the points C, D, are in phase. The impedances at the ports must also be similar.

Figure 1a reproduces the ARRL Antenna Handbook illustration. Figure 1b shows the same configuration in which the co-axial cable connections between the ports B, C, D are shown dotted. There is one difference which is in the segment from AB. The object of this is to act as a balun and to prevent currents flowing on the outside of the feed cable. It is suggested that the performance of the balun or choke would not be affected if the connection of the outer of section BC to the balun conductor was omitted. The arrangement in Figure 1c shows that when this is done the cable break at B with its extra complication can be omitted. The choke conductor or set of conductors is connected to the outer conductor of the co-axial feed cable at the point A. The configuration analysed is shown at C. The balun is formed of 2 conductors, 0.36 cm diameter, on opposite sides of the co-axial cable and spaced with their axes, 4 cm from the cable axis. The antenna gain can be increased by repeating section CD each time adding one half wavelength of cable and one port. The final portion of the analysis deals with an antenna with 16 sections such as CD.

4 NUMERICAL ANALYSIS RESULTS

4.1 The ARRL Design

The arrangement shown in Figure 1d which is a simplified form of the ARRL design with feed cable and balun omitted was first analysed. The results: current distribution, input impedance and gain are shown in Figure 2. It will be noted that the gain is less than unity. An examination of a vertical cut in the far field pattern in Figure 3 shows that the maximum field strength is not in the horizontal plane. This suggests a lack of uniformity of phase of the current in the conductors and in Figure 2 a gradual change in current phase can be seen in the centre section CD. This is a sign of a travelling wave. In figure 4 the power flow is shown and it can be seen that when 1 Volt is applied 1.77 mW flows into port C. The power flow onto the conductors is 2.0 mW. At D power flows from the conductors into the port and co-axial line. This power flow along the conductor from C to D, is consistent with the gradual change of phase between C and D. The results suggest a lack of symmetry between top and bottom and the length of the top section DF which is the sum of a quarter wavelength in air plus a co-axial line of a quarter wavelength of cable is

longer than the lowest section CB. A further analysis was carried out with the length of DF reduced to a total of $\lambda/4$ air (the $\lambda/4$ cable can be contained in this). For symmetry the lowest section BC in Figure 1 was also made $\lambda/4$ air. Figure 5 shows the results of this analysis, there is now a positive gain and the phase of the current is uniform. The ARRL design is believed to be in error and the $\lambda/4$ air top section was retained for all the subsequent analyses.

4.2 Antennas with Repeated Centre Sections

A feature of the design is that the section CD can be repeated and gain in the horizontal plane can be increased. The next analysis was performed with an antenna having 2 sections such as CD, the feed cable again being omitted. The structure and the results obtained are presented in Figure 6. It will be seen that no greater gain is obtained than for the antenna with a single centre section.

Further analyses were carried out using 3, 4, 5, and 16 centre sections. The variation of gain with number of sections is shown in Figure 7 and the current distribution for 16 sections in Figure 9. In Figure 7 it can be seen that the gain approaches that of a uniform current distribution as given by Eq 1 of the Appendix when 4 or more centre sections are used. For 2 and 3 sections as seen in Figure 6 there is a lack of uniformity of phase in the current. Indeed there is a substantial length with reversed phase.

In Figure 9 it can be seen that whereas there is still a small fraction of the length in which the phase is reversed this is associated with low amplitude current and so the loss in gain is small. The loss of gain compared with the ideal uniform current that occurs with the smaller numbers of half wavelength sections is due to the periodic variation in current shown in Figure 9 not being established.

4.3 Cable and Balun

A balun together with 3.5 wavelengths of cable was connected to the lower end of the 16 centre section array. The balun was formed of two quarter wavelength conductors connected to the feeder cable outer at A (of Figure 1), The spacing of quarter wave conductor and cable was made large enough to satisfy minimum segment length restrictions of the numerical analysis, in practice a smaller spacing could be used. The segment layout and results are shown in Figure 10. The action of the balun in reducing current on the cable can be seen, the standing waves on the cable are 22 dB below those on the antenna. By comparison with Figure 9 it can be seen that the balun and cable do not affect gain.

4.4 Lossy Cable

In practice a small diameter cable with significant loss may well be used. Because there are standing waves in the antenna cable system a further analysis is required to assess the effective loss and the reduction of antenna gain. The analysis was carried out using the published loss (4) corresponding to the cable UR 43 at 160 MHz of 0.164 dB/m (5 dB/100') and using dimensions corresponding to 160 MHz. The results are shown in Figure 11 and the gain of 8.63 dB compares with the 10.69 dB in Figure 10 corresponding to the loss-free

cable. The gain calculated refers to that measured at the input port C (Figure 1) and the loss in the feed cable up to this point must be subtracted from the calculated gain.

4.5 Bandwidth

In order to indicate the bandwidth of the system analyses were performed at frequencies 5 MHz higher and lower than the design frequency of 160 MHz. The analyses were carried out using the lossy cable with balun and feed cable. The results for 165 MHz are shown in Figure 12 and for 155 MHz in Figure 13. The gains are substantially reduced to 7.39 and 3.88 dB respectively. It will be noticed that the standing wave amplitude on the feeder cables has increased. Although 160 MHz has been given as the design frequency, this only enters when specifying the loss of the feed cable. All dimensions otherwise are in wavelengths, the calculations at 155 and 165 MHz refer to an antenna with wavelength dimensions corresponding to 160 MHz.

4.6 Conclusion

The design of a co-axial array antenna proposed in the ARRL antenna handbook has been analysed. A defect in the design has been rectified and it has been shown that an array of overall length 5 1/3 wavelengths can have a gain of 10.69 dBI. The effect of cable losses on gain has been calculated and some analyses have been performed in antennas at frequencies 3% above and below the design frequency.

REFERENCES

1 ARRL Antenna Handbook.

2 Burke G, Poggio N, "Numerical Electromagnetic Code (NEC)", NOSC TD/116 Naval Ocean Systems Centre, San Diego, California.

3 Jasik H, "Antenna Engineering Handbook", McGraw-Hill, 1961.

4 Defence Standards 61/12, MOD.

5 Schelkunoff S, Friis H T, "Antennas", J Wiley, 1952.

APPENDIX

THE GAIN OF ARRAYS WITH NON-UNIFORM CURRENT DISTRIBUTIONS

Figures 7 and 9 show that although the current in the conductor system is non-uniform the gain obtained differs little from that which would be obtained with a uniform current distribution. To investigate this point the gain of an array of impulse current elements ie of finite current length product but infinitely short, was calculated as a function of the spacing of the elements. The impulse current element can be considered an extreme of a non-uniform current distribution. The gain g over an isotropic radiator of a uniform current carrying conductor of length L is given by (5).

$$g = \tfrac{1}{2}\left[\frac{\text{Sin } A}{A} - \frac{2 - \text{Cos } A}{A^2} + \frac{\text{Sin } A}{A^3}\right]^{-1} \qquad (1)$$

where $A = 2\pi L/\lambda$ and λ is the free space wavelength.

The total power P radiated by a linear array of n current elements of length δ tending to zero with finite current moment $I\delta$ and separated by ℓ found by integrating the field intensity ϕ over all directions.

$$P = \iint \phi \, d\Omega \qquad (2)$$

and using spherical co-ordinates r, θ, ϕ

and substitutes for

$$\phi = 15\pi \frac{(I\delta)^2}{\lambda} \frac{\text{Sin}^2(n\pi\ell \text{ Cos } \theta/\lambda) \text{ Sin}^2 \theta}{\text{Sin}^2(\pi\ell \text{ Cos } \theta/\lambda)} \qquad (3)$$

from reference (4) we find

$$P = 15\pi \frac{(\delta I)^2}{L} \int_0^1 \frac{\text{Sin}^2 \, kx}{N^2 \text{ Sin}(kx/N)} (1 - x^2) \, dx \qquad (4)$$

where L is the total array length of N elements.

The gain over an isotropic radiator is given by

$$G = 4\pi \, \Phi(\tfrac{\pi}{2}, 0)/P \qquad (5)$$

Values of G were calculated from Equations (4) and (5) by numerical integration for values of L the total length of the array in wavelengths in the range 10-100 while n the number of current elements varied from 1 to 100. The results are shown in Figure 14 and it can be seen that provided the spacing of

the current elements ℓ is less than one wavelength, the gain is substantially that of a uniform current distribution of the same total length.

This will also be true for distributions more uniform than the extreme impulse distribution and the tendency of the gain of the vertical array with more than 8 sections to approach that of the uniform distribution as shown in Figure 7 is consistent with this although as seen in Figure 9 the current is by no means uniform but is roughly periodic in one wavelength.

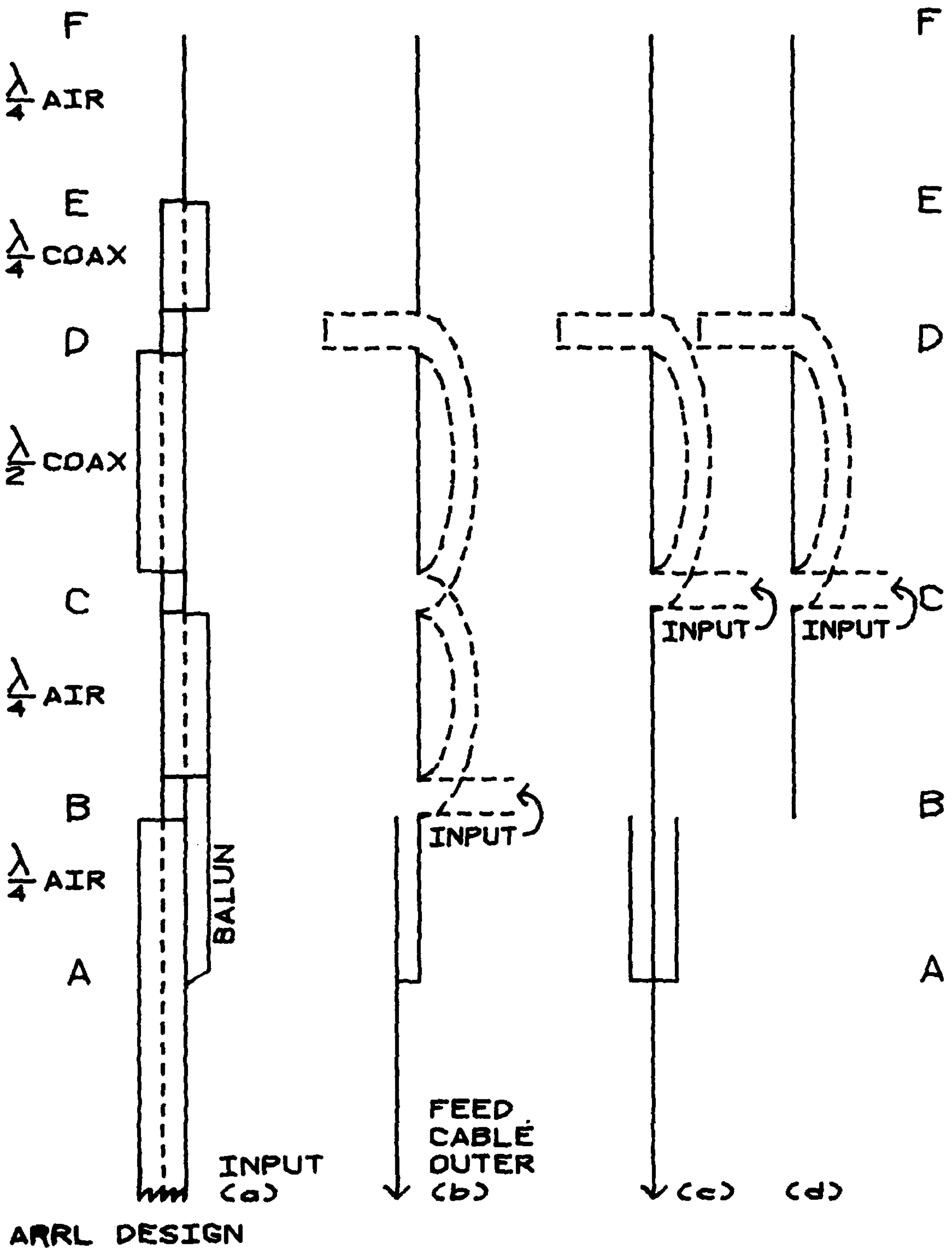

FIGURE 1. THE COLLINEAR VERTICAL ARRAY

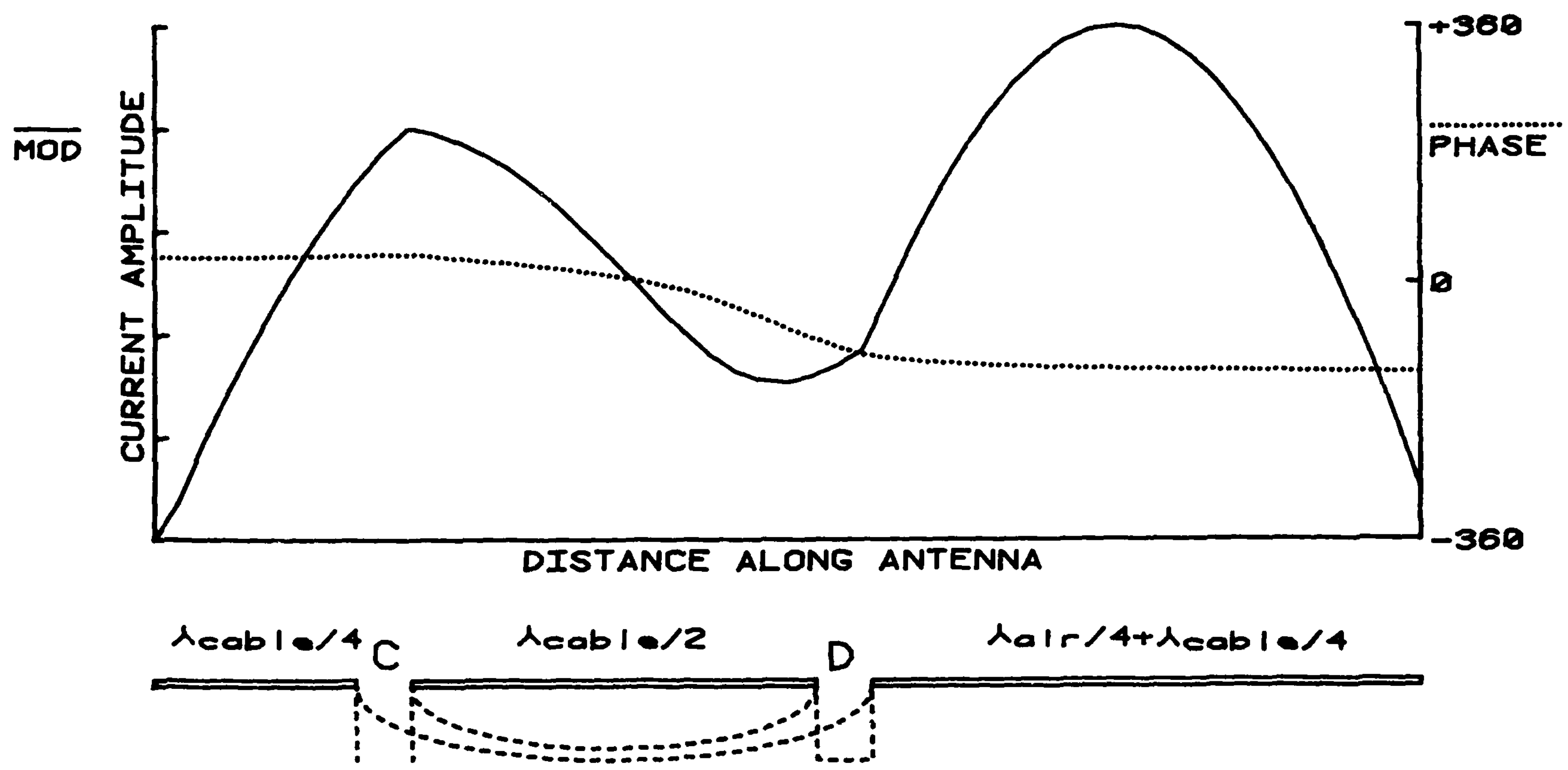

Figure 2. 1/6 1/3 5/12 (air) No balun
Cable Impedance=52 Ohms,Loss=0 dB/M,Velocity Ratio=.67
Antenna Impedance= 259.0 -76.9 j Ohms
Horiz. Gain =-2.46 dB

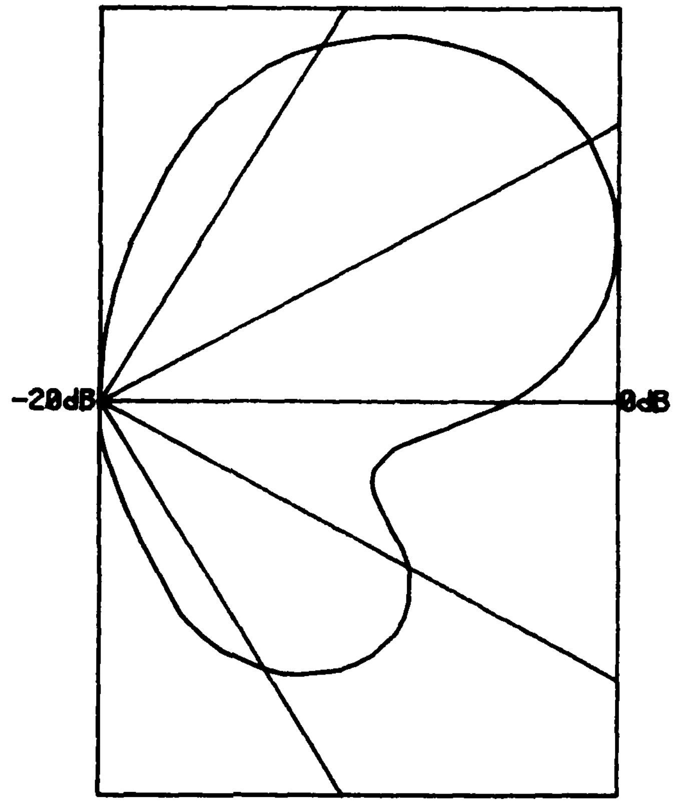

FIGURE 3. VERTICAL SECTION OF POLAR DIAGRAM
RESULT OF FIG.2.

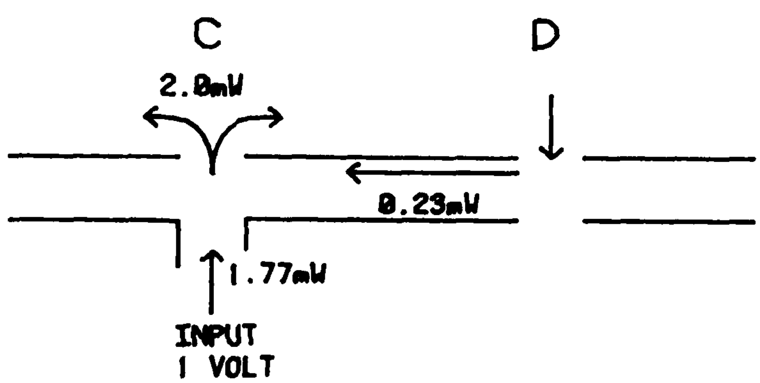

FIGURE 4. POWER FLOW.

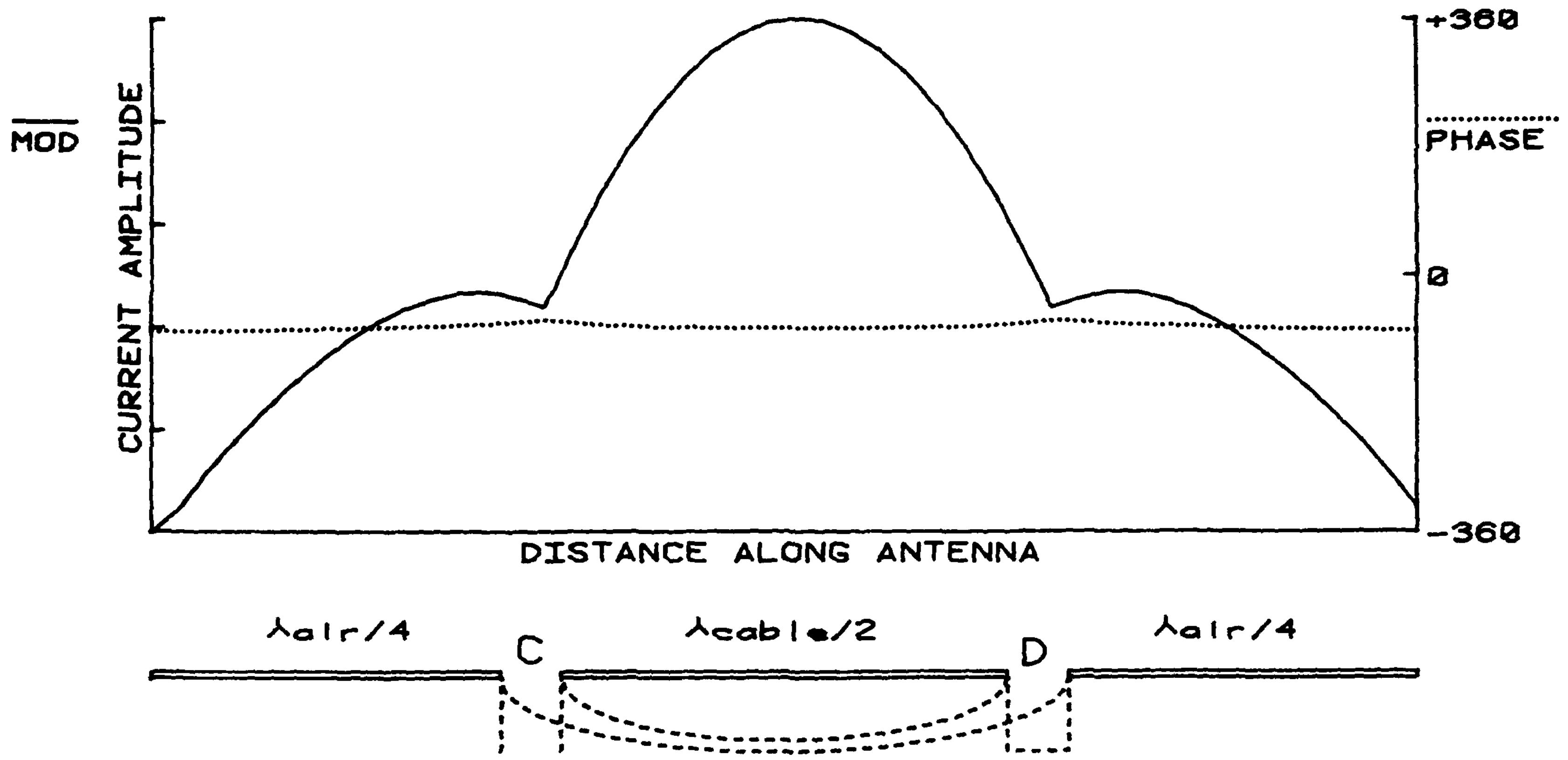

Figure 5. 1/4 1/3 1/4 (air) No Balun
Cable Impedance=52 Ohms, Loss=0 dB/M, Velocity Ratio=.67
Antenna Impedance= 154.8 +299.0 j Ohms
Horiz. Gain =2.75 dB

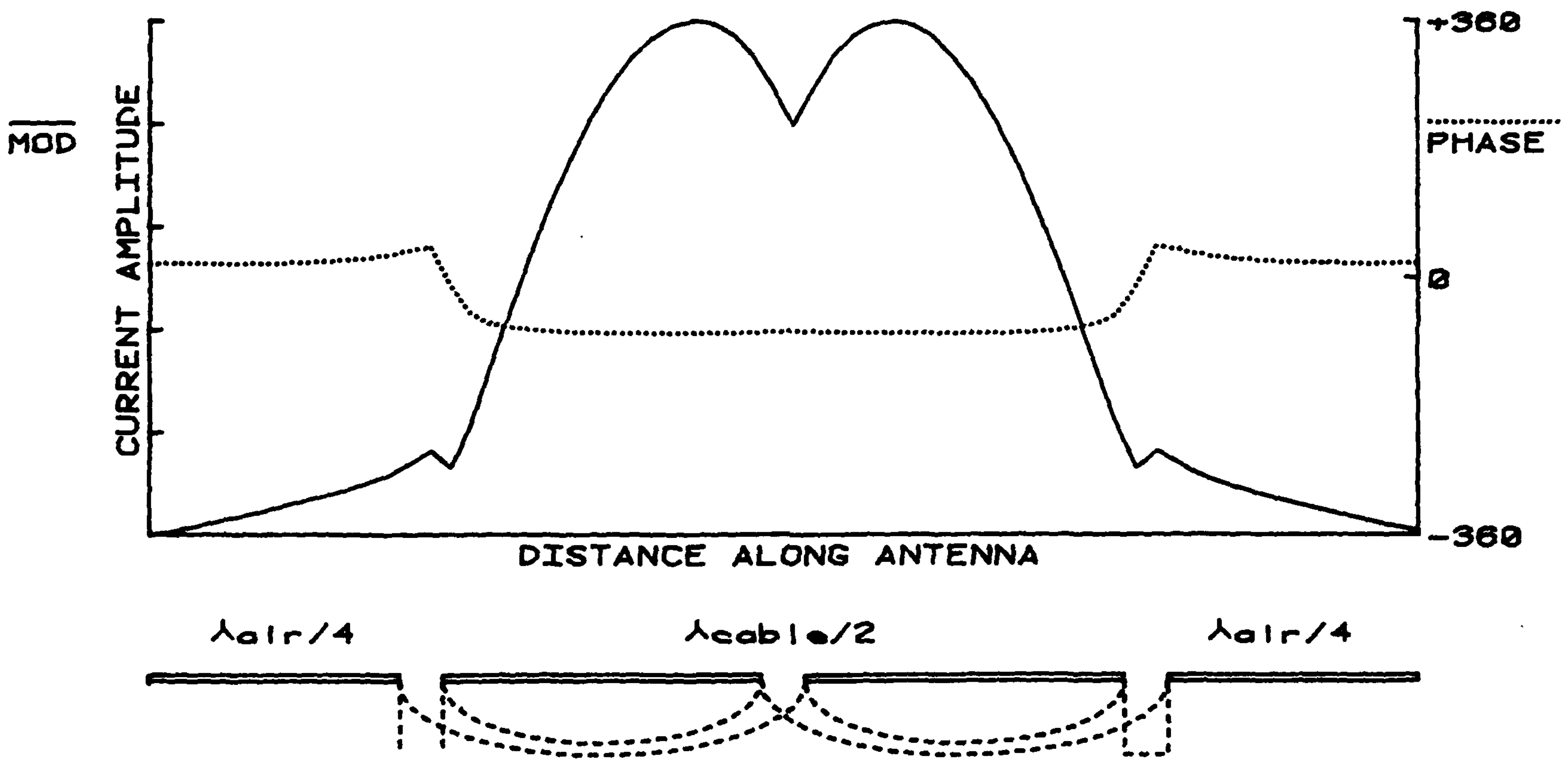

Figure 6. 1/4 1/3 1/3 1/4 (air) No Balun
Cable Impedance=52 Ohms, Loss=0 dB/M, Velocity Ratio=.67
Antenna Impedance= 292.0 +356.1 j Ohms
Horiz. Gain =2.44 dB

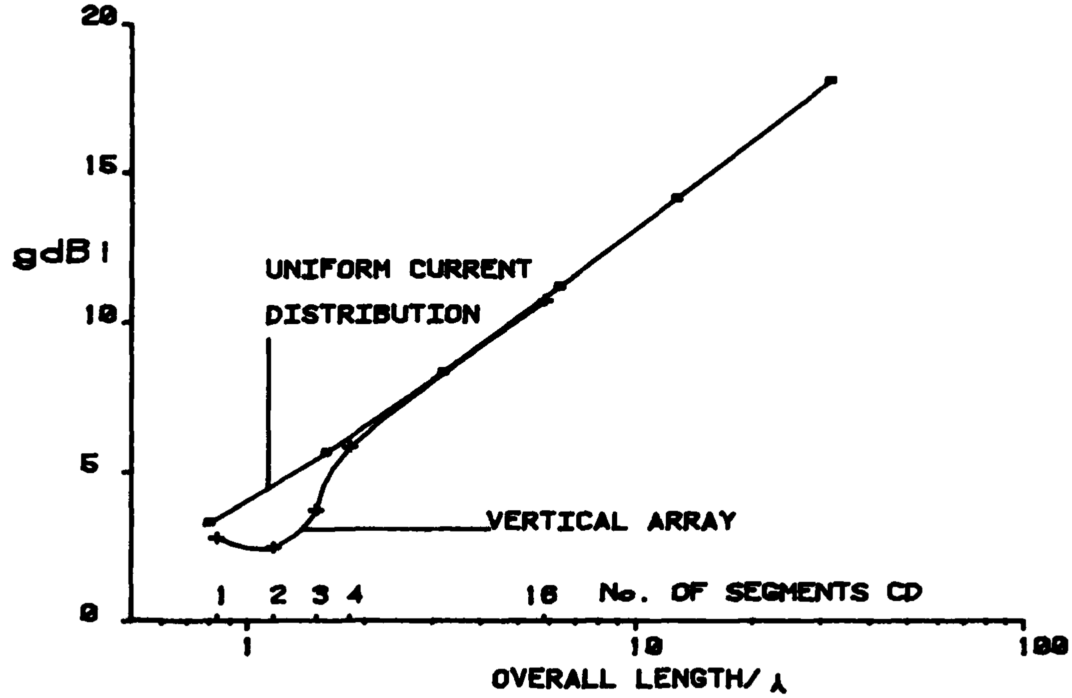

FIGURE 7. GAIN OF VERTICAL ARRAY COMPARED WITH UNIFORM CURRENT DISTRIBUTION.

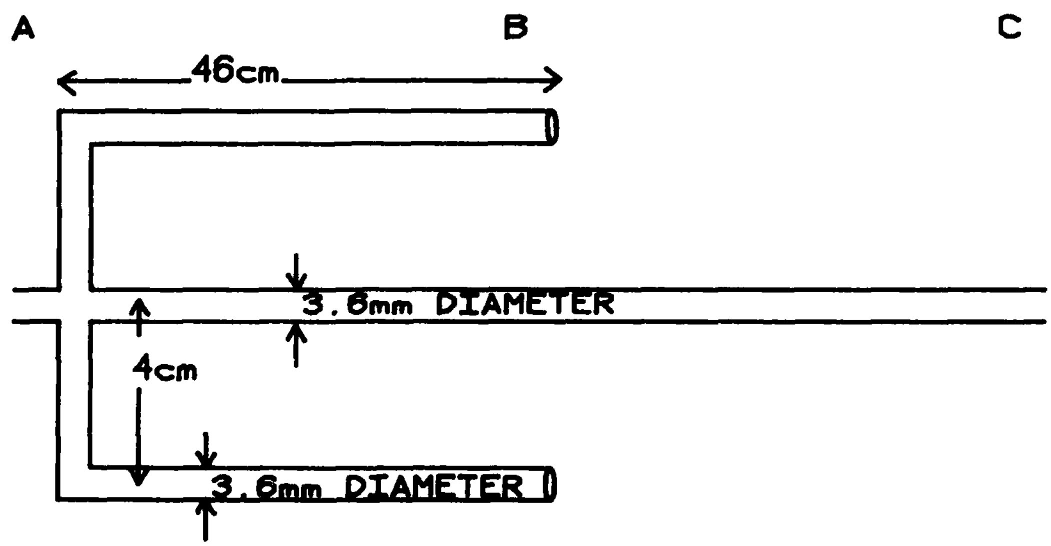

FIGURE 8. THE BALUN.

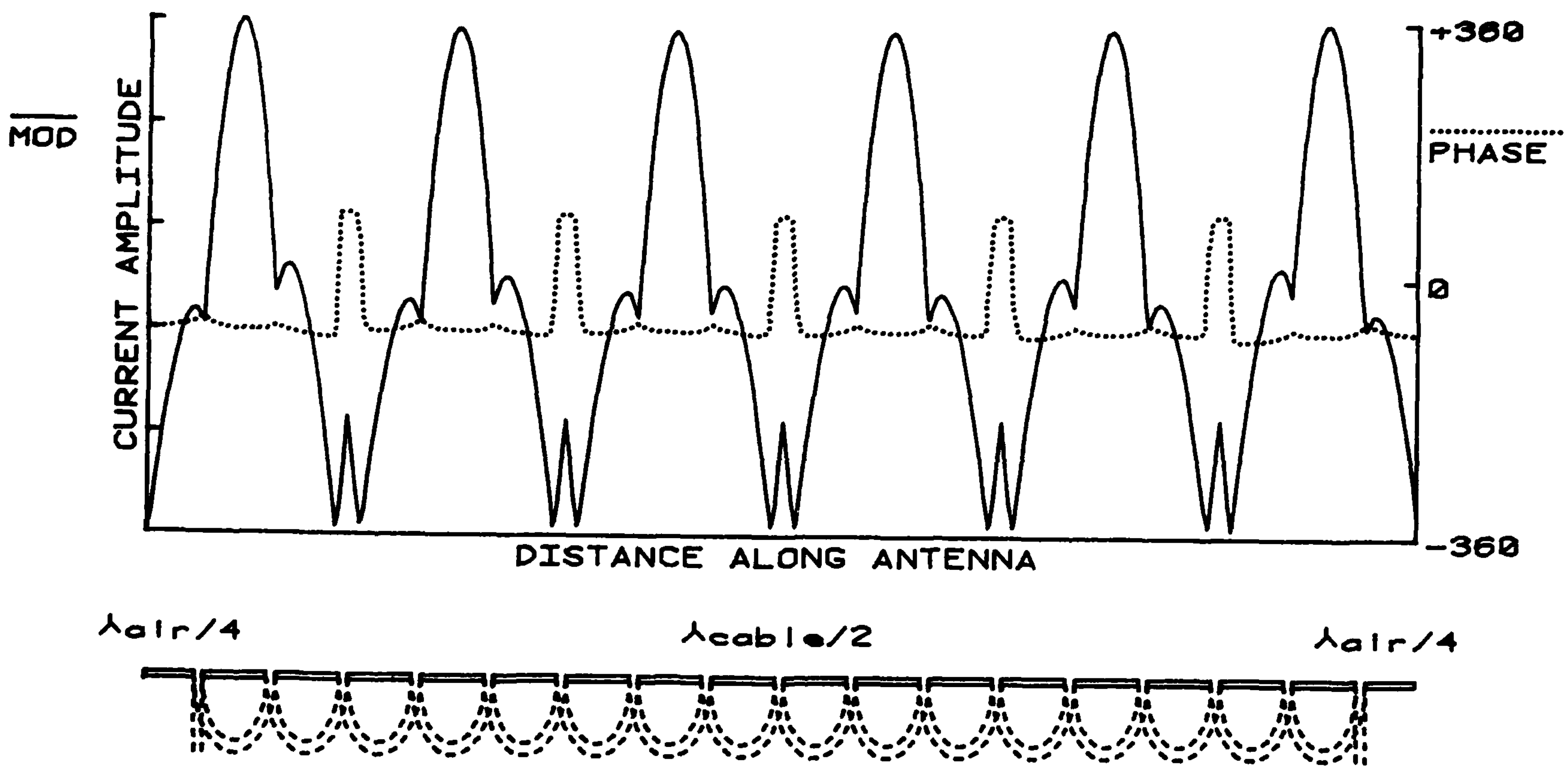

Figure 9. 1/4 (1/3)*16 1/4 (air) No Balun, No Cable Loss
Cable Impedance=52 Ohms, Loss=0 dB/M, Velocity Ratio=.67
Antenna Impedance= 39.9 +60.0 j Ohms
Horiz. Gain =10.69 dB

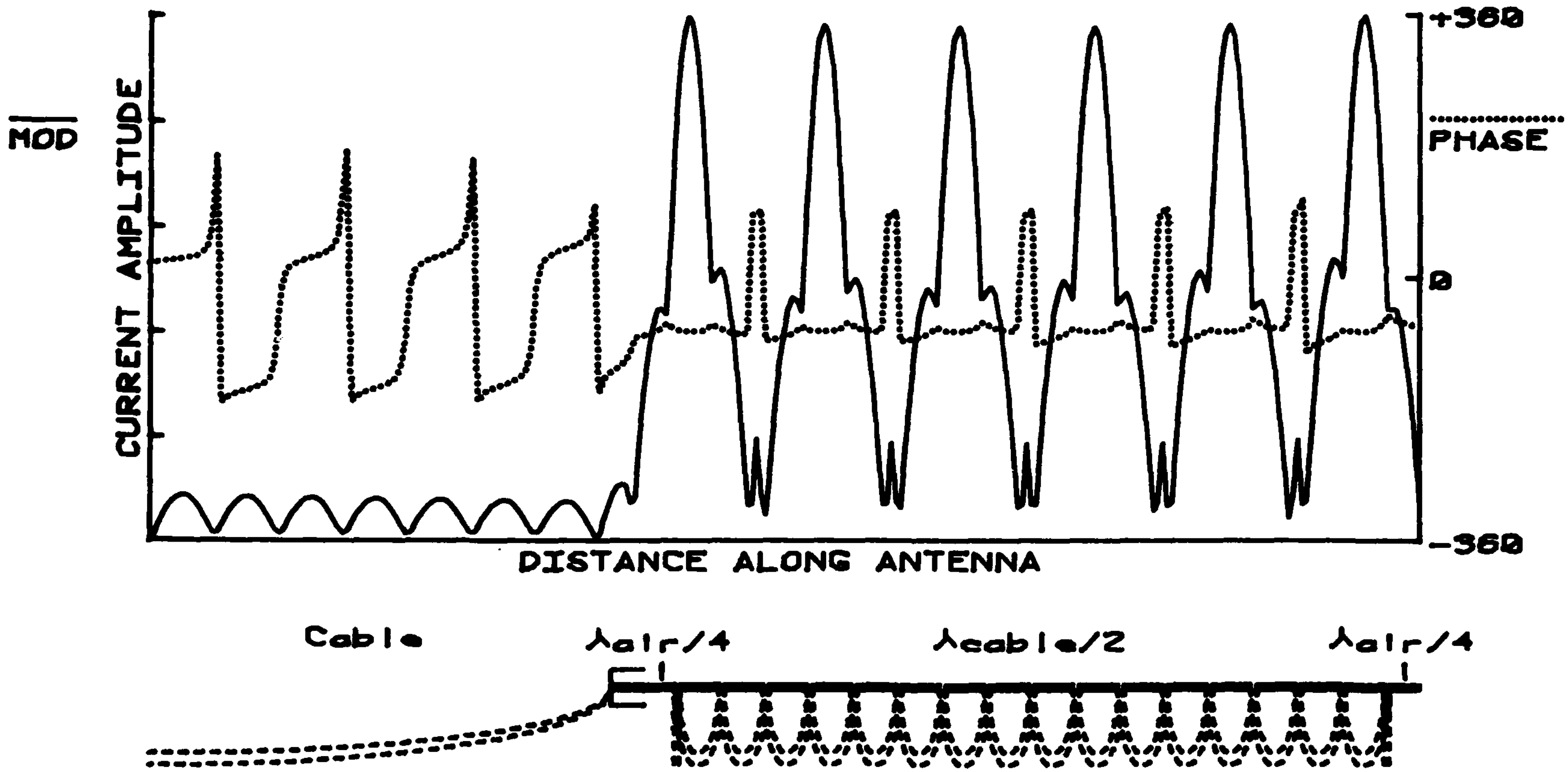

Figure 10. 6.5m Cable, Balun, 1/4 (1/3)*16 1/4, 100 MHz
Cable Impedance=52 Ohms, Loss=0 dB/M, Velocity Ratio=.67
Antenna Impedance= 34.5 +57.4 j Ohms
Horiz. Gain =10.69 dB

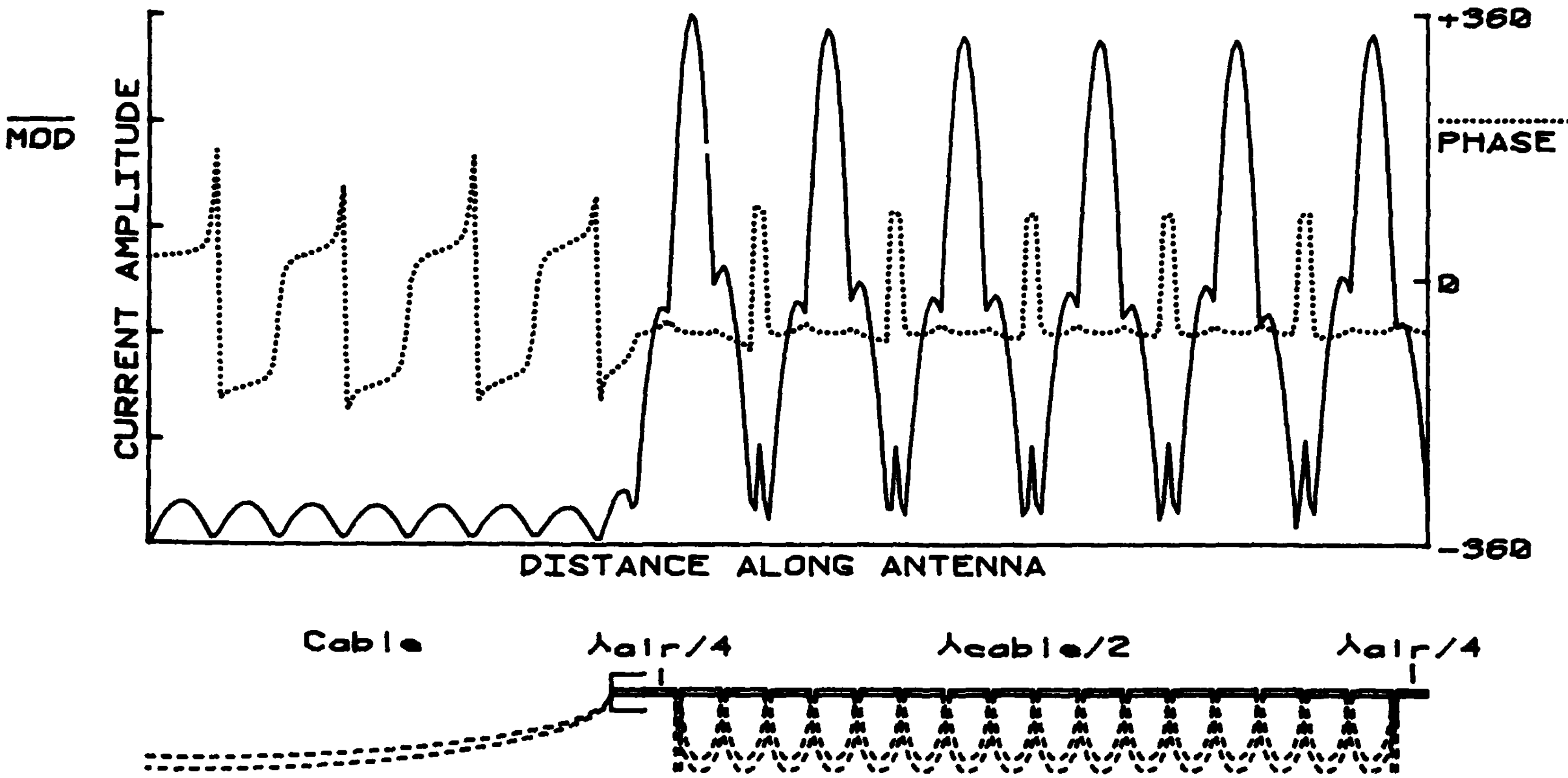

Figure 11. 6.5m Cable, Balun, 1/4 (1/3)*16 1/4, 160MHz
Cable Impedance=52 Ohms, Loss=0.164 dB/M, Velocity Ratio=.67
Antenna Impedance= 42.2 +43.5 j Ohms
Horiz. Gain =6.63 dB

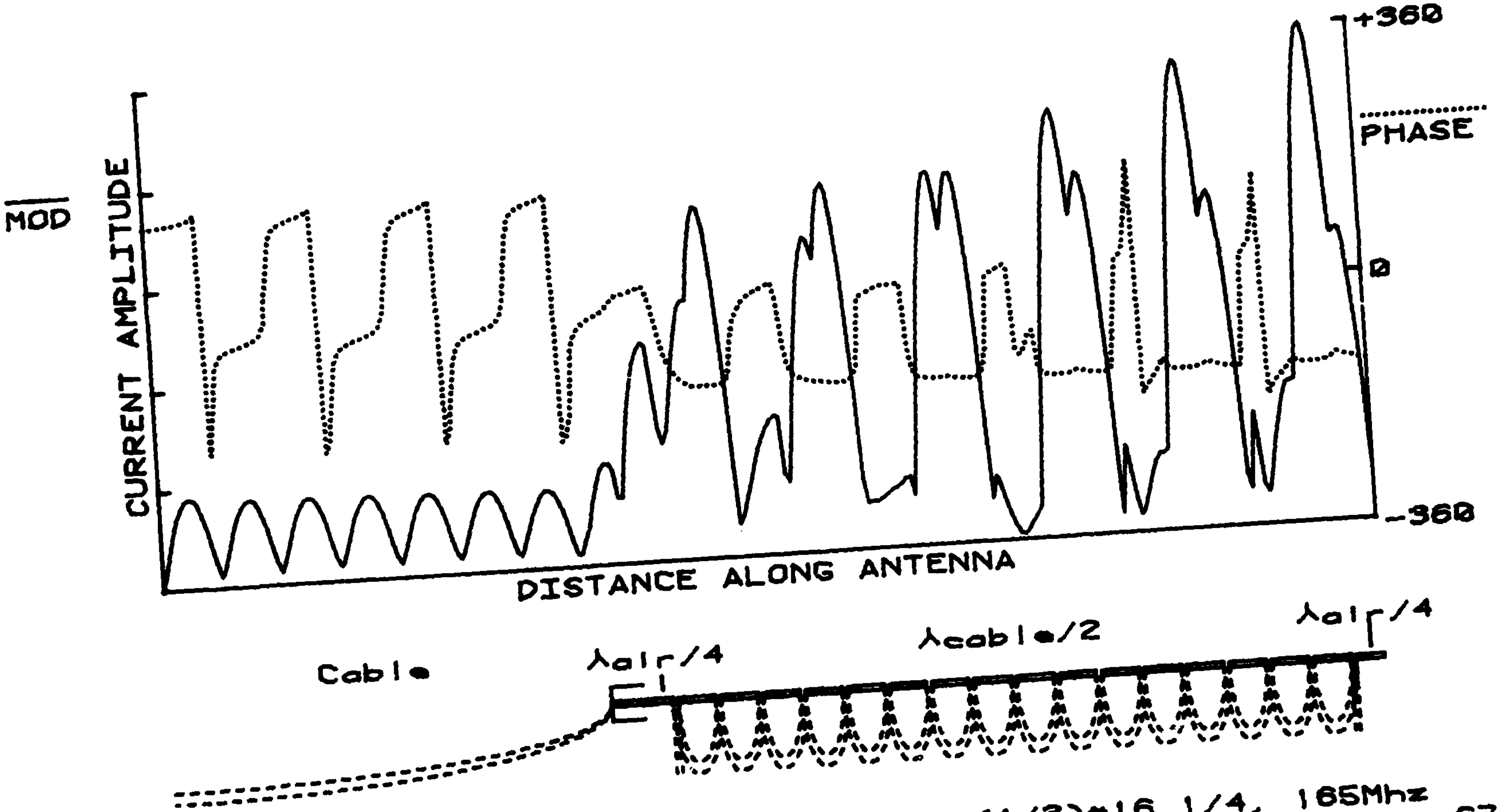

Figure 12. 6.5m Cable, Balun, 1/4 (1/3)*16 1/4, 165Mhz
Cable Impedance=52 Ohms,Loss=0.164 dB/M,Velocity Ratio=.67
Antenna Impedance= 27.4 -8.7 J Ohms
Horiz. Gain =7.39 dB

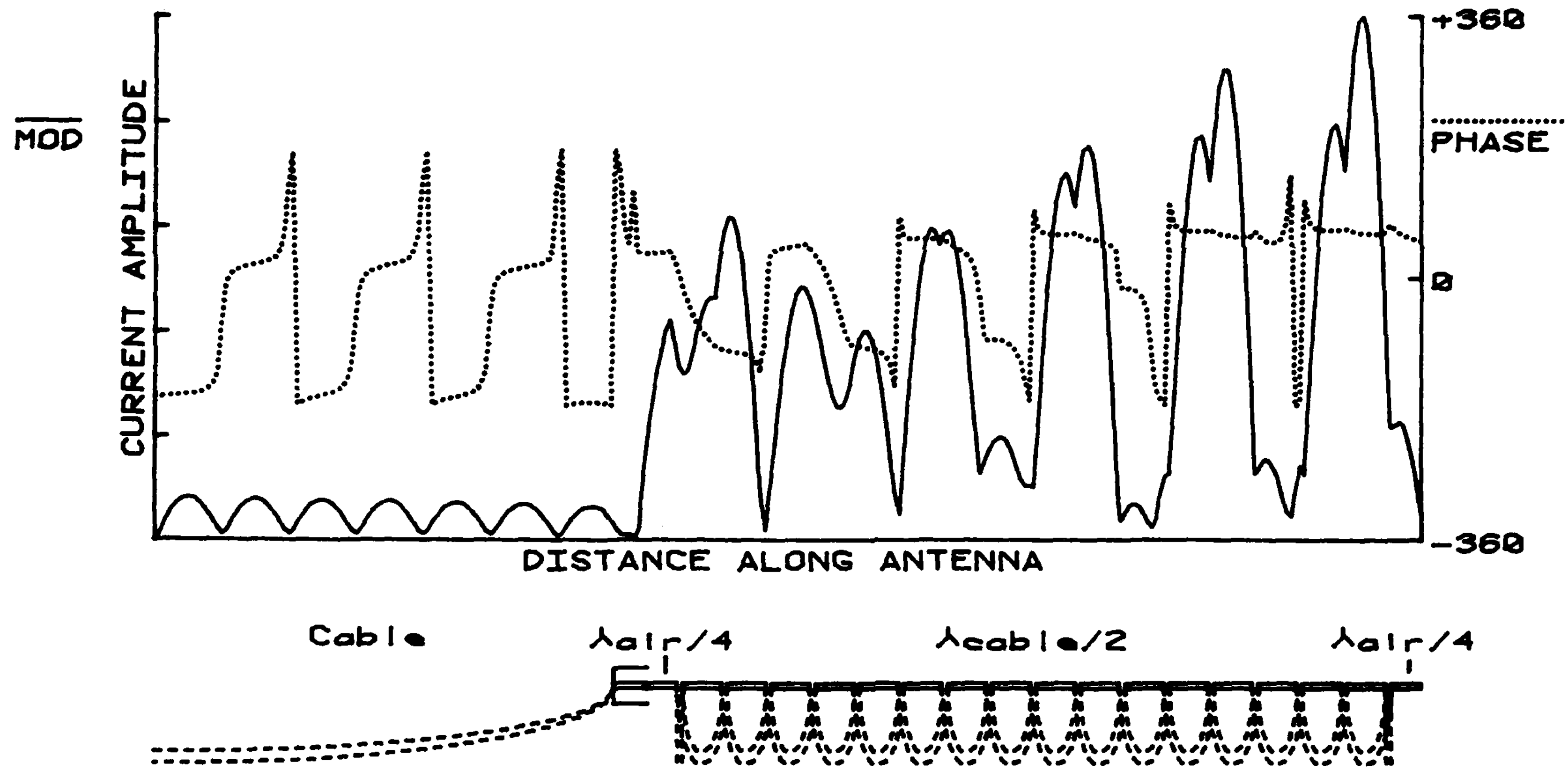

Figure 13. 6.5m Cable, Balun, 1/4 (1/3)*16 1/4, 155 MHz
Cable Impedance=52 Ohms, Loss=0.164 dB/M, Velocity Ratio=.67
Antenna Impedance= 15.5 -14.7 j Ohms
Horiz. Gain =3.66 dB

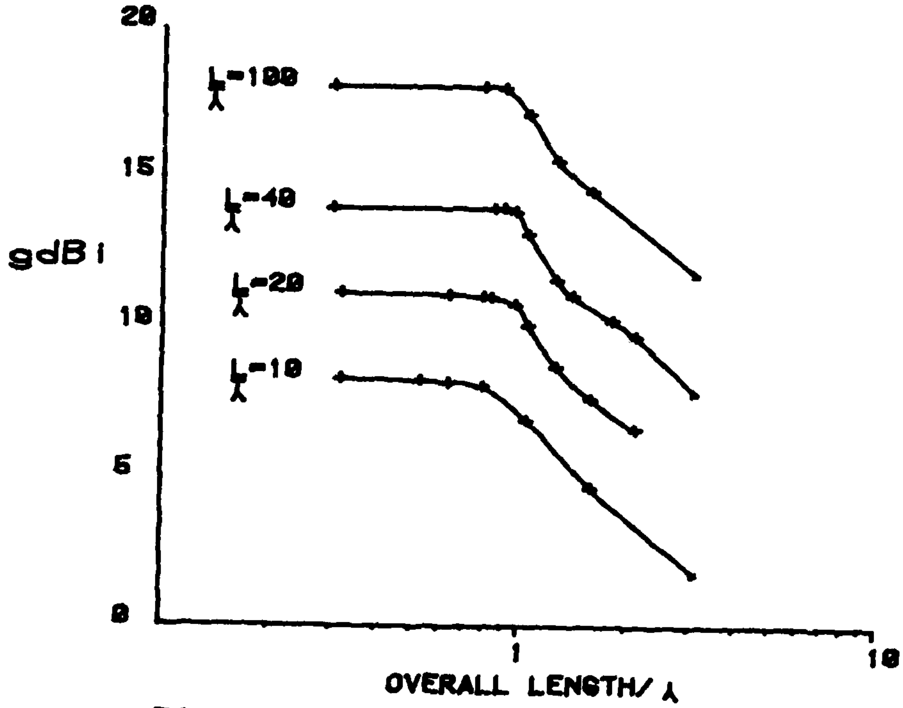

FIG.14 GAIN OF ARRAYS OF COLLINEAR EQUI-SPACED INFINITESIMAL CURRENT ELEMENTS

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